

Automated Launch, Recovery, and Refueling for Small Unmanned Aerial Vehicles

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ABSTRACT

Small unmanned aerial vehicles (UAVs) are hindered by their limited payload and duration. Consequently, UAVs spend little time in their area of operation, returning frequently to base for refueling. The effective payload and duration of small UAVs is increased by moving the support base closer to the operating area; however this increases risk to personnel. Performing the refueling operations autonomously allows the support base to be located closer to the operating area without increasing risk to personnel. Engineers at SPAWAR Systems Center San Diego (SSC San Diego) are working to develop technologies for automated launch, recovery, refueling, rearming, and re-launching of small UAVs. These technologies are intended to provide forward-refueling capabilities by teaming small UAVs with large unmanned ground vehicles (UGVs). The UGVs have larger payload capacities so they can easily carry fuel for the UAVs in addition to their own fuel and mission payloads. This paper describes a prototype system that launched and recovered a remotely-piloted UAV from a UGV and performed automated refueling of a UAV mockup.

Keywords: robotics, unmanned aerial vehicle, UAV, unmanned ground vehicle, UGV, autonomous, vertical take-off and landing, VTOL, refueling

1. INTRODUCTION

The Autonomous UAV Mission System (AUMS)¹ is sponsored by the Office of the Secretary of Defense's Joint Robotics Program (JRP)² and developed by a team of engineers at SSC San Diego. The AUMS is designed to provide current and future military programs with the capability to automatically launch, recover, refuel, rearm, and re-launch a small vertical takeoff and landing (VTOL) UAV. This capability will solve a problem that hinders the adoption and expansion of these platforms in the battlefield. Their utility is greatly diminished by their limited payload and duration. Since UAVs require frequent refueling, they spend less time in the field of operation, which reduces their effectiveness in many military environments. The effective payload and duration of small UAVs can be increased by moving the support base closer to the area of operation, but this increases risk to personnel. If the refueling and rearming operations can be performed autonomously, then the support base can be transported closer to the area of operation without increasing risk to personnel.

The AUMS development effort is divided into three major phases: 1) Launch and Recovery; 2) Refueling; and 3) Landing. The system is designed to take advantage of several technologies developed at SSC San Diego as well as other research institutions. These include SSC San Diego's Multi-robot Operator Control Unit (MOCU)³ and Network Enabled Resource Device (NERD)⁴, the JRP's Joint Architecture for Unmanned Systems (JAUS)⁵, highly accurate GPS technology from Geodetics, Inc.⁶, and precision vision technologies for landing from National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA JPL)⁷ and Carnegie Mellon University (CMU)⁸.

Development of the AUMS began at SSC San Diego in March 2002 with the first generation AUMS: a simple fiberglass prototype launch fixture. This was mounted on a Mobile Detection Assessment Response System (MDARS) UGV⁹ and used with an Allied Aerospace 29" iSTAR UAV (Fig. 1) for the first launch in Holtville, California. The iSTAR is a Future Combat Systems (FCS)¹⁰ Class III vehicle (Section 5) and has a Lift Augmented Ducted Fan

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(LADF) design that can be used for vertical takeoff and landing as well as high-speed horizontal flight. Payloads may be carried in the nose, duct, or tail section of the iSTAR.¹¹



Figure 1. Allied Aerospace 29" iSTAR UAV

In 2003, a second generation AUMS prototype was developed and demonstrated with the iSTAR for the JRP Working Group in December 2003. A bench demo of the automated refueling capability was conducted on September 15, 2004 using an iSTAR mockup. Vision technology from JPL was received in 2004 and integration of automated landing technologies is scheduled for 2005. The AUMS prototypes have been designed around the iSTAR platform, but future development will include other VTOL UAVs.

This paper describes the technical characteristics of the AUMS prototype, lessons learned and some of the military programs and applications that will benefit from this system.

2. PHASE ONE: LAUNCH AND RECOVERY

The launch and recovery component of the AUMS can be broken into two subcomponents: the landing pad and the refueling/release mechanism. The design of these two subcomponents has been influenced by the results of two phases of testing and the resulting analysis and lessons learned. This section discusses design intent, experimental results, lessons learned and future plans.

2.1 First Generation Launch

The first generation AUMS shown in Fig. 2 consisted only of a vented launch pad. The system was not designed for landing the UAV and served only to test the launch of the UAV from a UGV. Testing proved the feasibility of the concept as well as generating some of the key issues that would need to be resolved to produce a reliable system for the launch phase. A critical issue was discovered during testing: as the engine speed of the UAV increased and the vehicle began to go aloft, small crosswinds would carry it to the edge of the launch pad causing it to tip over before gaining sufficient altitude to stabilize. To address this issue, a solenoid release latch was integrated into the center of the launch pad and a mating attachment point was affixed to the lower center body of the UAV. The release latch kept the UAV firmly attached to the landing pad until the UAV engine was at full power. With the addition of the release latch the UAV launched cleanly from the pad in minimal crosswind conditions. Once at the desired altitude and clear of obstacles on the ground the UAV was able to achieve stable flight. However, in nominal to considerable crosswind conditions, the UAV could easily be swept into low altitude obstacles, such as UGV antennas, when launching.



Figure 2. First Generation AUMS with MDARS

Another issue uncovered during testing was the impact of the ground effect on the UAV when operating in close proximity to the UGV. Ground effect is a common occurrence experienced by any aerial vehicle generating aerodynamic lift within close proximity to a surface below it, typically the ground or in this case the landing fixture mounted on top of the UGV. The downward airflow generated by the lift fan was reflected off of the UGV predominantly back towards the UAV which tended to push the UAV away from the landing pad during its final approach. The arrows in Fig. 3 represent the field of ground effect created by UAV/UGV interaction. The irregularity of the upper surface of the landing pad and UGV in addition to external environmental effects creates an unpredictable ground effect. This results in turbulence as well as the push described above, further complicating the UAV's final approach. It is anticipated that minimizing ground effect in future designs will make landing much easier. Fortunately, during launch, the ground effect helps the UAV get aloft more quickly. Future testing with the second generation landing pad will help to determine the potential benefits of having a solid pad to maximize ground effect for takeoff which is then reconfigured to a vented pad in an attempt to minimize the ground effect prior to the UAV's approach and landing.



Figure 3. Ground Effect Illustration with Second Generation AUMS on MDARS

2.2 Second Generation Launch and Recovery

The second generation AUMS (Fig. 4) was designed to accommodate a modular and reconfigurable launch and landing pad to permit a flexible testing regime. This redesign also attempted to address the adverse effects of crosswinds and ground effect discovered during the first generation of AUMS. The second generation design incorporated recovery and refueling capabilities, which are discussed in Section 2.3.



Figure 4. Second Generation AUMS with MDARS

To address the effect of crosswind during launch, the system was designed to be reconfigurable into a tube that enclosed the UAV. This design permitted the UAV to gain enough momentum and height to clear low altitude obstacles before it was affected by crosswinds. Fig. 5 illustrates the tube formation with UGV enclosed.



Figure 5. AUMS Tube Launch Formation

Testing of the tube launch concept quickly made it clear that this design had deficiencies. As the UAV left the tube its low speed caused the crosswinds to push it into the side of the tube. Friction between the outer duct of UAV and tube wall created an angular moment on the UAV. Upon exiting the tube, the angular moment was too great to be stopped by the UAV's control thrust and the UAV would quickly U-turn, crashing into the ground. A low friction Teflon® impregnated surface was added to the inside of the tube surfaces but it still did not improve the performance of the design. In order for the tube launch concept to work, the UAV needed to reach a much greater velocity before exiting the tube. Solutions for increasing the velocity include increasing the tube length, increasing the power of the UAV, or providing the UAV a boost from another system. Lengthening the tube is not a viable solution for use on a UGV and increasing the power of the UAV is currently outside the scope of the project. Future design and testing will explore boosting techniques and likely abandon the tube launch design.

Landing the UAV into a tube is impractical due to the small diameter of the tube. In order to support landing, the system was designed to reconfigure by adjusting the four quadrants of the tube. Each quadrant was hinged at the base and then actuated to allow the quadrants to be shifted from a vertical to near horizontal position or anywhere in between. Fig. 6 illustrates a 45° quadrant location. By testing at different angles of opening, landing the UAV into a funnel type pad could now be attempted. The funnel formation provided a larger diameter landing surface than a tube and assisted in centering the UAV on the landing pad. The funnel-type landing concept was subject to similar crosswind issues as those encountered with the tube launch, but to a lesser degree. If a strong wind blew the lower section of the UAV into one of the quadrants of the fixture during landing there was a potential for the UAV to tip. The funnel quadrants assisted in landing the UAV in a couple of instances; however it became apparent that a large, flat

landing pad would be more advantageous. Future designs will incorporate a landing pad that expands to a larger diameter for landing, and contracts to a smaller diameter, gently pushing the vehicle towards the center, for transportation and refueling of the UAV.



Figure 6. AUMS in 45 degree configuration

2.5 Second Generation Refueling/Release Mechanism

The refueling/release mechanism was designed to facilitate automatic capture, refueling, and release of the UAV. After the UAV lands, a linear actuator raises the coupling system until the coupler, integrated on the UAV, and the center mechanism mate. This activity is assisted by the passive centering cone which is free to slide up to an inch in any direction in the horizontal plane. The arms guide the UAV to within the one inch tolerance of the coupling system when the UAV lands. When the UAV is attached to the landing pad, refueling is accomplished by the same mechanism as the capture mechanism. When the coupler has successfully mated, a limit switch is activated and the actuator stops. As a safety back up a force sensor is located under the linear actuator. If for any reason the coupler does not mate, any significant forces will be transmitted to the force sensor and the actuator will be shut down before the center mechanism damages the UAV. After a successful coupling, the actuator is lowered to apply tension to the UAV, seating the UAV firmly on the landing pad (Fig. 7). Tension forces are calibrated by the force sensor and redundantly confirm a positive coupling. At this time refueling can commence. Refueling is discussed in Section 3.

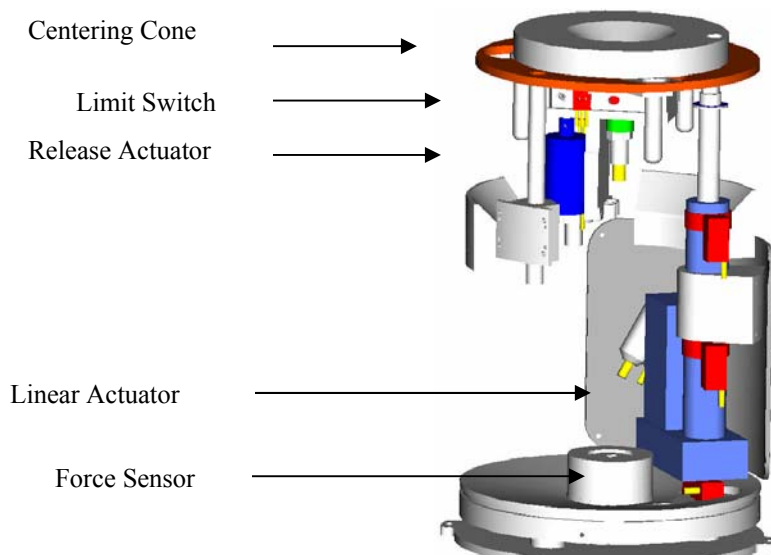


Figure 7. Internal Parts of the Refueling/Release Mechanism

After refueling is complete, the UAV is ready for launch. When the UAV reaches its maximum thrust, a release actuator activates the outer collar of the fuel coupler, releasing the UAV. Restraining the UAV until it reaches maximum thrust facilitates a quick, smooth take off. The design of the system accommodates any radial orientation of the UAV. The UAV can be rotated any direction in the vertical axis and the center mechanism will still function as designed.

3. PHASE TWO: REFUELING

The refueling subsystem consists of a gasoline-compatible pump, fuel level sensor, flow sensors, overflow sensors and leak detection sensors (Fig. 8). In the initial prototype, the subsystem refuels the UAV to a precise level without the use of an onboard fuel level indicator. The elimination of an airborne fuel level indicator decreases the subsystem complexity and allows for greater flexibility when integrating with different types of UAVs. When the UAV is connected to the refueling subsystem, the fuel is completely drained from the tank of the UAV. Then, starting from a known empty condition, the UAV is filled to a user-configurable volume. Fuel volume and flow are accurately computed from the flow sensors in real-time. The pump is automatically stopped once the commanded fill volume is reached. The elimination of an airborne fuel level indicator decreases the subsystem complexity and allows for greater flexibility when integrating with different types of UAVs.

Early in the design process, it was determined that partial refueling of the UAV would be necessary for practical mission capability. Partial refueling is a common practice where a UAV is refueled to some fraction of its total capacity. The reduction in fuel weight permits the UAV end-user to install heavier payloads than would be permissible with full mission endurance. The refueling subsystem and control algorithms include support for this mode of operation.

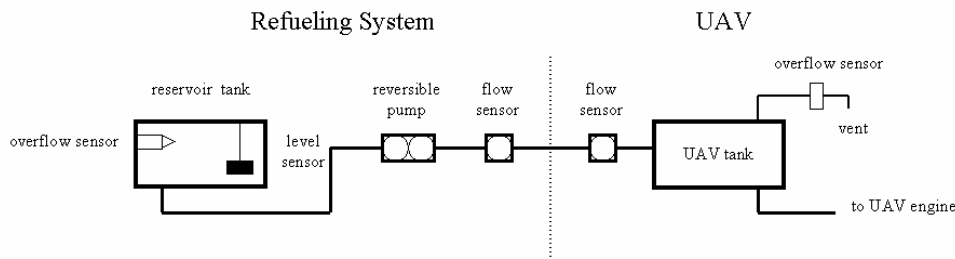


Figure 8. Refueling System Block Diagram

The refueling subsystem leveraged SSC San Diego's NERD to electronically monitor and control refueling operations and to achieve network interoperability. The NERD is an integrated electronics box with a RISC-based processor that is paired with a Field Programmable Gate Array (FPGA) to provide configurable, digital input/output. In this application, the FPGA is used to acquire, signal condition, and process real-time inputs from the various sensors without overtaxing the processor. The processor is then able to easily handle user requests while monitoring fueling progress on a supervisory level. Furthermore, the reconfigurable FPGA enables rapid prototyping of logic circuits minimizing the need to build specialized hardware.⁴

The safe and autonomous operation in the presence of volatile fuels was the primary concern during design of the refueling subsystem. Each component that came in contact with fuel was scrutinized for failure modes and possible ignition sources. Several techniques are used to ensure the safe handling of fuel. First, the spillage of significant fuel is prevented by monitoring the flow of liquid using redundant sensing methods. For example, if the flow sensor and corresponding level sensor rate of change did not agree, then a leak is likely. In addition, the refueling mechanism is built with integral sumps designed to capture and contain spilled fuel. Sensors placed in the bottom of the sumps are

able to detect small amounts of spilled fuel, which signals valves to close and pumps to shut off in order to prevent further spillage.

The selection of sensors and pumps meeting the refueling system requirements was critical to the operation of the system. The refueling pump (Fig. 8) needs to be gasoline safe, reversible, and capable of delivering fuel at approximately one gallon per minute. After an extensive search, only uni-directional gasoline-safe pumps were uncovered. Although not intended for reverse operation, the Mallory fuel pump selected for this application functioned adequately in both directions. A search for a truly bi-directional, gasoline-compatible pump is ongoing. Similarly, a bi-directional gasoline-compatible flow sensor in the specified flow range could not be found. A uni-directional sensor meeting all the other requirements was used instead. Although inaccurate, the flow sensor was not damaged by continuous flow in the reverse direction. In the reverse direction, the flow sensor was only used to determine if the airborne tank was empty. Thus, the sensor's imprecise measurements in the reverse direction were sufficient. In the forward direction, the sensor produced accurate and repeatable flow measurements. A system of actuated valves was proposed to attain bi-directional flow while keeping flow across the sensor and pump unidirectional. This system was not used due to the additional complexity in comparison to the increased performance that would have been attained.

SSC San Diego plans to continue to develop the refueling subsystem by acquiring an autonomous helicopter produced by Rotomotion, LLC.¹² Using the vehicle's interface, information about the fuel status of the air vehicle will be delivered to the refueling system. Prior knowledge of the vehicle's fuel status will enable faster fueling and shorter turn-around times. Furthermore, a data exchange between the air vehicle and refueling platform will permit the exploration of fault tolerant fueling algorithms including redundant leak, level, and overflow detection. This interactive behavior will increase the performance, reliability, and safety of the refueling subsystem.

4. PHASE THREE: LANDING

Autonomous landing of a VTOL UAV presents a challenge for the AUMS. The AUMS fixture needs to be very compact in order to fit onto a variety of UGV and USV (Unmanned Surface Vehicle) platforms without constraining the operation of these vehicles. This requires that the UAV be capable of very precise, three dimensional navigation in order to ensure accurate repeatable landings with extremely low position error relative to the fixture. Furthermore, this highly accurate relative position must be updated at very fast rates to account for UAV dynamics as well as environmental factors affecting the UAV approach and landing.

For the development and testing of various technologies, SSC San Diego acquired an assortment of small inexpensive VTOL aircraft. This assortment includes several hobby class radio-controlled helicopters, a Bergen Intrepid gas fueled helicopter¹³ (Fig. 9), a Micro Autonomous Systems, LLC LADF HeliSpy¹⁴ (Fig. 10), and an Allied Aerospace iSTAR described in the introduction. All of these aircraft, with the exception of the iSTAR, are tele-operated. In the near future SSC San Diego plans to acquire a JAUS compliant, autonomous helicopter produced by Rotomotion, LLC. (Fig. 11).

SSC San Diego teamed with Geodetics, Inc., CMU, and JPL to further develop and test existing technologies that may be capable of providing the high navigation accuracy required to accomplish the landing task. These existing technologies will be tested to determine the merit of the various approaches compared to a benchmark standard, such as the Novatel Inc. OEM4 GPS.¹⁵

SSC San Diego has extensive experience in the use of the OEM4 GPS on various UGV and USV platforms. The OEM4 is a state-of-the-art differential GPS (DGPS) system utilizing Real Time Kinematic (RTK) technology that offers absolute position accuracy of 1 - 2cm. This high absolute position accuracy is not necessary for the AUMS operations where the key is high relative position accuracy between the UAV and the fixture on the UGV. It does make the OEM4 extremely useful as a development and testing tool to use as a baseline for measuring the accuracy of other technologies. However, the OEM4 does have some significant drawbacks that could be problematic if it were used as the primary navigation tool for the landing phase in a deployed AUMS. Among these are the length of time to acquire a signal for re-establishing an accurate position fix should the system lose its position for some reason, the need for an accurately positioned base station to provide the required differential correction factors, and the high cost of the equipment. These drawbacks are the motivation for the investigation of alternative technologies to help solve the landing problem.



Figure 9. Bergen Intrepid



Figure 10. MASS, LLC HeliSpy



Figure 11. Rotomotion Helicopter

Geodetics, Inc. developed a GPS based software application that provides high relative accuracy with errors of less than 10 centimeters in preliminary testing. The system utilizes low cost GPS receivers with one or more designated as base receivers. For the AUMS application, the base receiver is located on the UGV that carries the AUMS launch fixture. Since the base receiver is located on a dynamic platform, its absolute position cannot be determined with a high level of accuracy, but the relative position of the GPS receiver located on board the UAV can be determined extremely accurately. The Geodetics system is described as an Epoch-by-Epoch™ system in which this high level of relative position accuracy can be resolved from a single sample from each receiver. This means that the Geodetics system does not suffer from the lengthy signal acquisition time that is a problem with RTK DGPS systems such as the OEM4. The time to set up a system in an unfamiliar environment is decreased because, unlike the OEM4, there is no need to place the base receiver at an accurately surveyed position.

CMU developed a vision-based positioning system that relies on infrared (IR) beacons arranged in an asymmetrical pattern on the UGV which carries the AUMS launch fixture. The UAV routinely transmits an omni-directional sync pulse that triggers the IR beacons on the UGV to output an IR pulse. One or more IR cameras located on the UAV detect these IR pulses and measure a relative bearing (azimuth and elevation) from the UAV to each of the beacons. An algorithm captures these relative bearings and computes the relative position of the UAV. The algorithm also detects the asymmetry of the beacon pattern and from this can deduce the relative heading of the UAV. In testing the system has produced repeatable relative positions with errors of less than 10 centimeters. The range of the system is limited by the ability of the camera to detect and resolve relative bearings to the beacons. The spacing between the beacons determines the precision level that the system can provide. This system will only be useful for navigation of the UAV in close proximity (within 10 meters) to the AUMS landing pad and will supplement a GPS-based navigation solution.

The NASA JPL vision system is an extension of the Smart Camera board developed for SSC San Diego to provide a miniature stereo vision capability for small mobile robots. The work on the Smart Camera has been leveraged by the AUMS project to provide a small, light-weight, vision-based target tracking capability. The camera board incorporates a CMOS imager, a DSP and an FPGA which make the Smart Camera a stand-alone system.

The JPL tracking application uses a fiducial target made up of four solid black circles on a white background arranged in a square with an intercircle spacing equal to twice the circle diameter. A possible future enhancement would utilize active infrared beams for the target. Once the target has been acquired, the tracking algorithm provides the full six degree-of-freedom pose estimate of the camera relative to the target at a rate of approximately 10 hertz. This relative pose estimate will be used in conjunction with other sensor data by the automated landing control software. Because the target is symmetric there will be an ambiguity of 180 degrees in the rotation about the z axis (yaw) of the pose estimate. This is easily resolved using other on-board sensors such as a flux-gate compass.

The development, test, and integration of these various landing technologies will be the primary focus of the AUMS development in fiscal year 2005. The first phase of this testing will involve static testing in the lab to acquire baseline performance data on the various systems under a variety of controlled conditions. The next phase will be to perform dynamic testing utilizing in-house helicopter assets to evaluate how each system performs in a real world environment. It is assumed that none of these technologies alone will provide a robust and repeatable landing solution. The ultimate solution will presumably incorporate both GPS and vision. This ultimate solution will be tested again on helicopter platforms prior to being integrated onto a 29" iSTAR.

5. MILITARY APPLICATIONS

The use of AUMS for military applications is indicated in several current programs. Two of these programs are briefly described in this section. Each application seeks to take advantage of the extended capabilities that result from the teaming of UGVs and UAVs. Other military applications are anticipated as the AUMS development progresses.

5.1 Future Combat Systems (FCS)

The U.S. Army's FCS demonstration program focuses on the development of a network-centric multi-mission combat system. Its purpose is to be overwhelmingly lethal, strategically deployable, self-sustaining, and highly survivable in combat through the use of a Family of Systems. The goal of the program is to develop an ensemble of manned and unmanned ground and air vehicles that maximizes the following critical performance factors: ground platform strategy, operational and tactical mobility, lethality, survivability and sustainability. The program will be adaptable to missions ranging from warfighting to peacekeeping.¹⁶

An automated UAV mission system will address FCS requirements for UAVs deployed at all levels (Fig. 12). By incorporating UAVs with other manned and unmanned vehicles, coverage area and mission flexibility are greatly expanded. Since a UAV can be launched from one type of platform and recovered by another, the strengths that each type of platform offers are leveraged to accomplish a specific task or set of tasks.

An automated UAV mission system benefits the key FCS mission areas by providing better situational understanding and awareness, beyond line-of-sight targeting, and a wider surveillance and communications coverage area.



Figure 12. FCS UAVs

5.2 MDARS

The MDARS program is sponsored by the Office of the Program Manager, Force Protection Systems (PM-FPS) and is a joint development effort between the U.S. Army and U.S. Navy. The goal is to field mobile robots for physical security. MDARS provides intruder detection and assessment as well as other security capabilities including barrier assessment, and inventory accountability.

The MDARS platform (Fig. 13) is the UGV used for the AUMS development. The benefits of the AUMS would provide an extension to the MDARS mission areas. For example, an MDARS platform could autonomously patrol a weapons storage facility performing intruder detection. If an intruder was detected and attempted to elude the MDARS platform, the automated UAV mission system could launch the UAV in order to engage in pursuit of the intruder. The AUMS also allows the UAV to spend more time in the air for continuous aerial coverage by providing in-operation

refueling capability. This would expand the physical security system's mission of intruder detection by extending its zone of security.¹⁶



Figure 13. MDARS surveillance platform

6. CONCLUSION

UAVs are being adopted in the military at a fast pace, but while they bring many benefits to the battlefield, they also present logistical challenges. One of these challenges is how to deal with the short flight duration time of VTOL UAVs while operating in a critical area that is unsafe for humans. One solution is the use of an autonomous UAV mission system designed to launch, recover, refuel, rearm and re-launch a UAV. This capability will increase the effectiveness of VTOL UAVs while decreasing the risk to personnel and providing an enhanced awareness for security and battlefield operations. SSC San Diego is developing the AUMS in phases to minimize risk and to ensure that lessons learned are incorporated back into the development process. Future plans include development and integration of automated landing technologies, collaboration with other organizations that are developing complimentary technologies, and participation in Joint UGV-UAV experiments.

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